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6. AUTHOR(S) Julian D. Maynard				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The Pennsylvania State University Department of Physics 104 Davey Lab University Park, PA 16802			8. PERFORMING ORGANIZATION REPORT NUMBER	
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13. ABSTRACT (Maximum 200 words) This project involved the use of innovative acoustic techniques to study new materials and new developments in solid state physics. Major accomplishments include a) the preparation and publication of a number of papers, book chapters, and invited lectures b) the measurement and analysis of an aluminum alloy quasicrystal and its cubic approximant c) the use of resonant ultrasound to measure acoustic attenuation and determine the effects of heat treatment on ceramics, d) the extension of our technique for measuring even lower (possibly the lowest) infrared optical absorption coefficient, and e) the measurement of the effects of disorder on the propagation of a nonlinear pulse, and f) the observation of statistical effects in measurements of individual bond breaking events in fracture.				
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INNOVATIVE TECHNIQUES FOR STUDYING NEW MATERIALS AND NEW DEVELOPMENTS IN CONDENSED MATTER PHYSICS

This report summarizes the goals and accomplishments for ONR grant N00014-92-J-1186, "Innovative Acoustic Techniques for Studying New Materials and New Developments in Condensed Matter Physics". The goals of the project were a) to use resonant ultrasound spectroscopy to study new materials, such as quasicrystals and ceramics, b) to use a resonant photoacoustic technique to measure infrared optical absorption in highly transparent materials, c) to use acoustic analogs to study effects analogous to those of mesoscopic electronic systems, and d) the measurement of individual bond breaking events during the fracture of brittle materials.

Published papers, invited presentations, personnel, etc.

Accomplishments during the eight year period covered by this report include the publication of 20 refereed papers and nine book chapters, 51 invited lectures, and the presentation of 38 contributed papers at meetings. Of the 20 papers, five were published in the prestigious physics journal *Physical Review Letters*, and one was published in *Applied Physics Letters*. Four papers and book chapters have been submitted and are pending publication. Of the 51 invited lectures, 13 were university colloquia, 5 were seminars, and 19 were presentations at international meetings. Three patent disclosures were submitted, and one patent was awarded.

Three graduate students received Ph.D. degrees, and one received a Master's degree; all continued working in acoustics in the US. Five post doctoral scholars (including one female) were funded by the ONR; two are continuing their research, and of the three who left, two are continuing in acoustics in the US. A number of undergraduate students, including five females, have made significant contributions to the research.

During this period Professor Maynard was awarded the Silver Medal in Physical Acoustics by the Acoustical Society of America. An invited paper, "Resonant Ultrasound Spectroscopy," was published in the science magazine *Physics Today*. An invited tutorial lecture on Anderson Localization was presented at the prestigious International School on Physics of Semiconducting Compounds, Ustron-Jaszowiec.

A list of the publications, personnel, etc. is presented in the appendix. In the sections which follow, a summary of the research accomplishments is presented; in these sections, references will be made to the papers, presentations, etc. in the appendix.

Development of Small Sample Resonant Ultrasound Spectroscopy

Elastic constants, like spring constants, may be measured with a static technique, in which a displacement is measured as a linear response to a small applied force. However, it was long ago learned that a better method is to measure an elastic vibration, as found, for example, in a propagating sound wave. Most existing complete sets of elastic constants for materials have been determined by measuring the time of flight of sound pulses. Recently, a

relatively new method, resonant ultrasound spectroscopy (RUS), has been developed. In the RUS method, rather than measuring sound velocities, one measures the natural frequencies of elastic vibration for a number of normal modes of a sample, and processes these in a computer, along with the shape and mass of the sample. With the single measurement and computer processing, all of the elastic properties, including attenuation, may be determined. Professor Maynard was involved in the original application of the method in the physics community, and was invited to write a review article on RUS for *Physics Today* [Appendix, Paper 11.]

A major contribution of this ONR funded research has been the extension of the RUS method to allow measurements on very small samples. Such measurements require very small, broadband, and high sensitivity transducers. A successful technique was developed using piezoelectric film, with a thickness as small as 9 microns. With this technique, samples only ~ 100 microns in size, with masses of less than 100 micrograms, may be measured. This accomplishment has been described in detail in several publications and invited lectures; Graduate student Phil Spoor produced an excellent review of the RUS technique in an ONR Technical Report. [In the appendix, see Papers 1, Book Chapters 8, Technical Report 2, and Invited Presentations 2, 10, 22, 29, 30, 39.]

Measuring the Isotropy of a Quasicrystal with Resonant Ultrasound Spectroscopy

One of the fascinating properties of quasicrystals is that, unlike conventional crystals, quasicrystals are elastically isotropic. For conventional crystals with high symmetries (e.g. cubic crystals), many physical properties are isotropic, but the property of linear elasticity is fundamentally anisotropic. Thus it is interesting that icosahedral quasicrystals, having long-range order like conventional crystals, must be isotropic in sound propagation. Measuring these properties experimentally has been challenging, because while conventional crystals are fundamentally anisotropic, their elastic constants may be numerically very close to those of an isotropic material, so that it is difficult to distinguish between intrinsically isotropic and anisotropic behavior in a measurement. In our research we used small sample RUS to obtain high precision measurements of the elastic constants of both the quasicrystalline and periodic approximant phases of AlCuLi and found, with a significant level of confidence, that the quasicrystalline phase is isotropic (differing from the most nearly isotropic conventional crystal by ten standard deviations), while the periodic approximant is not. This measurement provides an important landmark for the RUS technology, because it represents a measurement for which conventional ultrasonic methods failed; RUS was necessary in order to determine all of the elastic constants self-consistently (without having to remount transducers), with high precision, and for very small samples. Details of the research on quasicrystals was published in *Phys. Rev. Lett.*, other journals, and in Phil Spoor's Ph.D. thesis (an ONR Technical Report). [In the Appendix, see Papers 5, 10, and Technical Report 2.]

In order to obtain the best precision, it was necessary to account for the deviation of the sample from an exactly rectangular parallelepiped. While this could be done with the standard formulation of RUS analysis, it was found that numerical problems appeared. Some problems were solved with subtle program repairs, but others were of a more fundamental

nature. Graduate student Phil Spoor reported on these aspects of RUS in an invited talk at the May 1996 meeting of the Acoustical Society of America, and they formed a major part of his Ph.D. dissertation.[In the appendix, see Invited Presentation 30 and Technical Report 2.]

RUS Measurements on High Temperature Superconductors, Ceramic Particles, and Ultra-Hard Materials

The first application of RUS in the physics community was a collaboration with A. Migliori of Los Alamos National Lab in measuring the properties of material used in high temperature superconductors.[Appendix, Book Chapter 2.]

Another application of the small sample RUS technique was in a study of "proppants", used for oil recovery and solar receivers. The elastic constants and attenuation were measured for various heat treatments, and a peak in the attenuation at 1100 C that coincided with a minimum in Young's modulus was discovered; it was thought to be due to the appearance and subsequent healing of internal microcracks. Our attenuation measurements were based on graphical determinations of Q for a representative mode of vibration, which was not straightforward since the imperfect, spheroidal proppants tended to have multiple overlapping resonances. Subsequently we developed nonlinear curve-fitting software to satisfactorily model all the peaks in each cluster, determining the Q of each very precisely. We were thus able to unambiguously confirm the correlation between the heat-treatment effects and the acoustic properties. A paper on these results will be prepared in the future, in collaboration with John Hellmann of the College of Earth and Mineral Science.

The small sample RUS technique was also used to measure the elastic constants of titanium diboride, a material whose hardness (nearly as hard as diamond) and high electrical conductivity make it useful in many technological applications. This research was reported in the prestigious journal Applied Physics Letters.[Paper 15 in the appendix.]

Calculating Fluid Loading for RUS Measurements under Pressure

One application of RUS is to determine the shift in the elastic constants of a material subjected to high stress, generated by placing a sample in a gas at high pressure. A problem which results is that at high pressures the surrounding gas is at a sufficiently high density (and acoustic impedance) so that the sample vibrating in a normal mode at resonance radiates a significant amount of sound into the surrounding gas, and the radiation of sound energy lowers the quality factor of the RUS resonance and shifts the frequencies (fluid loading). At the suggestion of Dr. Logan Hargrove, methods developed in earlier ONR research, leading to the invention of Nearfield Acoustic Holography (NAH), were applied the problem of RUS fluid loading, and a method for calculating the effects was developed. This research was presented in several invited lectures and book chapters.[See Book Chapters 5, 9, and Invited Presentations 34, 35, 49.]

Application of RUS for Thin Films

With the development of mesoscopic and nanoscale electronic systems, there is currently great interest in the properties of the thin films which form the environment for the electrons. Diamond-like carbon and carbon nanotube films have also attracted attention for use as protective and lubricating coatings, etc. As with bulk solids, important properties include elastic constants and acoustic attenuation, which may be related to the electron-lattice coupling, magnetic effects, and mechanical properties. Surface Acoustic Waves (SAW) have been used to probe the properties of thin films, but with limitations since SAW cannot excite every elastic mode of the film, a limitation that can be overcome with RUS.

By using RUS and comparing the normal mode frequencies of a specimen before and after film deposition, the elements of the elastic tensor and attenuation coefficients of the thin film material may be determined. In order to detect the properties of a thin film using RUS, it is necessary that the substrate supporting the film not dominate the measurement. Thus small (thin) substrates are necessary, and our unique small sample RUS technique is essential.

In order to determine the elastic properties of a thin film on a substrate, the conventional (bulk sample) RUS software had to be modified. This has been accomplished, and simulations employing this software have been used to test the feasibility of the technique. It has been found that the fractional shift of the sample resonant frequencies due to the film is approximately equal to the fraction of the sample thickness occupied by the thin film. Thus a film of 100 nm thickness on a 100 micron thick substrate will shift the frequencies by about one part in 1000.

In the basic RUS technique for thin films, the substrate must be measured with and without the thin film, thus the sample must be mounted in the RUS apparatus at least twice. However, remounting a sample may result in some shift of the frequencies due to slightly different orientation and loading. In order to determine the properties of the thin film precisely, the shift due to remounting must be significantly less than the shift due to the thin film. After numerous trials, we have found the shift in frequencies due to remounting is less than one part in 10,000. However, it has been found that temperature scans result in more data, so that data fits can be used to determine the temperature dependence of the frequencies to one part in 100,000. Thus we can determine the properties of a 100 nm film on a 100 micron substrate to a precision of 1%. The software development and numerical tests of the feasibility of the research were the subject of the Master's dissertation of P. Jason White and an invited lecture.[Technical Report 3, Invited Presentation 47.]

Anderson Localization and Nonlinear Waves

Many of the invited papers and presentations have involved research with classical analogs of quantum mechanical phenomena, in particular Anderson localization.[See Papers 4, 7, Book Chapters 3, 4, 6, and Invited Presentations 3, 5-9, 12-15, 19, 21, 23-26, 28, 31-32, 37-38, 40, 42, 44, 46, 48, 50.] More recent research involves the effects of nonlinearity.

The study of systems which are both disordered and nonlinear is a relatively new frontier. Most of the research to date is theory, with significant contributions by mathematicians. A fundamental question is whether or not Anderson localization is weakened by the effects of nonlinearity. A survey of the theory papers shows that about half of the papers predict that Anderson localization is weakened by nonlinearity, and about half predict that it is not.

While the different predictions by the theory papers would seem to indicate a controversy, there is in fact no contradiction, because the conclusion depends on how the question is posed. For example, one may study the wave mechanics of a system by exciting it with a continuous wave, $\cos(\omega t)$, and examining the transmission spectrum, $S(\omega)$. On the other hand, one may launch a pulse into the system and study the temporal response at an exit point, $T(t)$. In a linear system the two results would be simply related by a Fourier transform. However, this is no longer true for a nonlinear system, and different results may be obtained. Current theory predicts that for continuous wave excitation of a 1-D nonlinear disordered system of length L , eigenstates remain localized and $S(\omega)$ for $\omega > 0$ decreases exponentially with L .

The theoretically predicted behavior for a pulse in a nonlinear disordered system is more interesting, and might be described with a simple picture as follows. For a linear 1-D disordered system, the behavior of a pulse is rigorously found by making a product of matrices from one end of the system to the other, and as predicted by rigorous theory, the eigenstates would be localized and the transmitted pulse energy would decrease exponentially with L . However, a nonlinear pulse has an extra degree of freedom which may be adjusted to satisfy conditions locally, over some characteristic length, i.e. the "width" of the pulse. If the width of the pulse is much less than the Anderson localization length, then the disorder has no effect and the pulse is transmitted without the exponential decrease. If the pulse width is sufficiently greater than the localization length, then transmission is exponentially decreased. When the width of the pulse is on the order of the localization length, then the pulse travels some distance with a slight decrease before an exponential decrease begins.

In order to study nonlinear pulse propagation experimentally, we used surface waves on a fluid because they are intrinsically nonlinear (the speed of the surface wave depends on depth, which is modified by the presence of a finite amplitude wave). Surface waves in superfluid helium films were used to reduce viscous damping which would weaken long range phase coherence in the linear regime; water surface wave experiments suffer dramatically from the limitations of damping. Our research with nonlinear waves led to two publications in Phys. Rev. Lett. and an invited symposium lecture at a meeting of the American Physical Society, and was the subject of Vernon A. Hopkins' Ph.D. dissertation. [See Papers 3, 8, 12, 13, 16, 17, 20, Dissertation 4, and Invited Presentations 1, 4, 11, 16, 18, 20.]

Measurement of an extremely low (possibly the lowest) bulk infrared optical absorption

One of the acoustic innovations developed in our research program is a resonant photoacoustic technique for measuring optical absorption in highly transparent crystals and glasses. Such highly transparent materials are important for applications in optical fiber long distance

transmission lines, in lenses and windows for high-power laser systems, and in electro-optic, magneto-optic, and acousto-optic components for optical computers, etc. The optical absorption in new materials is so small that it has become difficult to measure in conveniently sized (~ 1 cm) samples. One of the most sensitive methods for measuring optical absorption is the photoacoustic technique, which usually requires a high power pulse laser. Our resonant photoacoustic technique uses a continuous (CW) laser which has less power than a pulse laser, but nevertheless has orders of magnitude improved sensitivity in measuring optical absorption. This technique may be used to measure optical absorption coefficients as small as 10^{-8} cm^{-1} . A crucial feature of our technique is that the CW laser may be modulated at a frequency corresponding to an acoustic resonance of the sample, and when driven at resonance, the sample itself acts as a natural amplifier with a gain equal to the quality factor (Q) of the resonance. This gain occurs before the transduction, so that the transducer noise is not amplified. Since highly transparent samples are often made with high purity material, such samples will also have high mechanical Q's, at least 10^4 and as high as 10^6 . The gain which arises by driving the sample at a high Q resonance more than compensates for the lower laser power, and results in ~ 100 times improved sensitivity. Furthermore, with CW modulation, very low noise phase sensitive detection may be employed.

The minimum in the absorption of electromagnetic radiation occurs at about $1 \mu\text{m}$; indeed the absorption is so small here that no previous measurement has been able to detect any absorption. With the use of a Nd:YAG laser, with a wavelength just above $1 \mu\text{m}$, we have applied the resonant photoacoustic technique to study infrared absorption, and have been able to measure an optical absorption coefficient of $2 \times 10^{-7} \text{ cm}^{-1}$ in CaF_2 . This should establish our technique as the record holder for optical absorption measurement. This research formed the basis for the Ph.D. degree of Wei-li Lin, was published in the J. Acoust. Soc. Am., and was presented in invited talks. [See Paper 2, Technical Report 1, Invited Presentation 27, 36.]

Fracture Research

The objective of the research on fracture was to use innovative acoustic measurements to improve contemporary models which address fracture in brittle materials having random bond strength distributions, such as concrete, ceramics, composite materials, etc.

A current theory for fracture models a brittle material as a network of bonds which are distributed randomly in the network with some probability distribution. Fracture is simulated by applying a stress or strain at the boundaries of the bond network; at some value of the boundary load, one of the internal bonds will break, increasing the load on the remaining bonds, and the process continues until the sample breaks in two. A deficiency in the model is that when a bond breaks, the calculation proceeds as though the new equilibrium stress field is established essentially at once, whereas in reality changes in the stress field must propagate away from the broken bond at no more than the speed of sound. Thus some dynamics are omitted in the model.

In order to provide a test of the random bond model and the effects of dynamics, it is necessary to have a measurement which can detect individual bonds breaking prior to and

during the catastrophic fracture. For the usual materials used in the study of fracture (glasses and resins), it would be impossible to detect individual atomic bonds breaking. However, it would be possible in a macroscopic model of a brittle solid. For this purpose an open cell carbon foam material having struts with lengths on the order of 1 mm has been studied. The struts play the role of the random bonds in the statistical physics models. When this material is placed in water, the water completely permeates the sample, and sound from a breaking interior strut propagates through the water in the open sample to an array of transducers outside the sample. With the array of transducers, triangulation permits individual bond breaking events to be localized in space as well as time.

The research revealed that as the stress on the sample was increased, the number of bonds on the verge of breaking increased. When one bond broke, it launched a stress wave which, because of internal friction, could only propagate a certain distance. If the distance between other bonds on the verge of breaking was less than this propagation distance, then the stress wave could trigger other bonds to break, and an avalanche of breaking bonds would result. This occurred just prior to the catastrophic fracture of the sample. These results were published in Physical Review Letters, and presented in an invited lecture at a meeting of the Acoustical Society of America.[See Paper 18, Invited Presentation 51 in the appendix.]

APPENDIX: PUBLICATIONS, PRESENTATIONS, ETC.

PAPERS PUBLISHED IN REFEREED JOURNALS

1. J. D. Maynard, "Using Piezoelectric Film and Acoustic Resonance to Determine the Complete Elastic Tensor in One Measurement", *J. Acoust. Soc. Am.* **91**, 1754-1762 (1992).
2. C. Yu, M. J. McKenna, J. D. White, and J. D. Maynard, "A new resonant photoacoustic technique for measuring very low optical absorption in crystals and glasses", *J. Acoust. Soc. Am.* **91**, 868-877 (1992).
3. M. J. McKenna, R. L. Stanley, and J. D. Maynard, "Effects of nonlinearity on Anderson localization", *Phys. Rev. Lett.* **69**, 1807 (1992).
4. J. D. Maynard, "A possible explanation of the discrepancy in electron persistent current amplitudes: A superfluid persistent current analog", *J. Low Temp. Phys.* **89**, 155-159 (1992).
5. P. S. Spoor, M. J. McKenna, and J. D. Maynard, "Using acoustic resonators to study superfluid-filled silica aerogel, high T_c superconductors, and quasicrystals", *J. Low Temp. Phys.* **89**, 689-693 (1992).
6. M. J. McKenna, T. P. Brosius, and J. D. Maynard, "Observation of two-stage layering transitions for solid ^4He on graphite", *Phys. Rev. Lett.* **69**, 3346-3349 (1992).
7. J. D. Maynard, "Classical analogs of mesoscopic quantum phenomena", *Physica B* **194-196**, 231-238 (1994).
8. M. J. McKenna, Justin Keat, Jun Wang, and J. D. Maynard, "Experiments on nonlinear wave propagation in disordered media", *Physica B* **194-196**, 1039-1040 (1994).
9. V. A. Hopkins, M. J. McKenna, and J. D. Maynard, "Anderson localization of ^3He with variable disorder provided by a ^4He solid/liquid interface", *Physica B* **194-196**, 1137-1138 (1994).
10. P. S. Spoor, J. D. Maynard, and A. R. Kortan, "Elastic isotropy and anisotropy in quasicrystalline and cubic AlCuLi ", *Phys. Rev. Lett.* **75**, 3462-3465 (1995).
11. J. D. Maynard, "Resonant Ultrasound Spectroscopy", *Physics Today* **49**, 26-31 (1996).
12. V. A. Hopkins, J. Keat, T. Zhang, and J. D. Maynard, "Observation of the predicted behavior of nonlinear pulse propagation in disordered media", *Phys. Rev. Lett.* **76**, 1102-1105 (1996).
13. T. Zhang, B. Bennett, V. A. Hopkins, and J. D. Maynard, "Effects of finite amplitude fields on superfluidity", *Proc. 21st Intl. Conf. Low Temp. Phys., Czech. J. Phys.* **46**, 145 (1996).

14. T. Zhang, B. Bennett, V. A. Hopkins, and J. D. Maynard, "Using liquid helium to study fluid interface coalescence effects", Proc. 21st Intl. Conf. Low Temp. Phys., Czech. J. Phys. **46**, 377 (1996).
15. P. S. Spoor, J. D. Maynard, M. J. Pan, D. J. Green, J. R. Hellmann, and T. Tanaka, "Elastic constants and crystal anisotropy of titanium diboride", Appl. Phys. Lett. **70**, 1959-1961 (1997).
16. L. C. Krysac and J. D. Maynard, "The role of convection during the self-focusing of nonlinear second sound pulses near the lambda point", J. Low Temp. Phys. **110**, 949 (1998).
17. V. A. Hopkins, L. C. Krysac and J. D. Maynard, "Experimental study of nonlinear continuous waves and pulses in disordered media showing Anderson localization", Phys. Rev. B **58**, 11,377 (1998).
18. L. C. Krysac and J. D. Maynard, "Evidence for the role of propagating stress waves during fracture", Phys. Rev. Lett. **81**, 4428 (1998).
19. B. Bennett, A. Shumays, L. C. Krysac, and J. D. maynard, "Noise from Raindrops: Fundamental Studies of Bubble Entrainment in Pure 4He", J. Low Temp. Phys. **113**, 1073-1077 (1998).
20. L. C. Krysac and J. D. Maynard, "Pulsed Nonlinear Sound in Superfluid 4He and 4He-3He Mixtures", J. Low Temp. Phys. **113**, 1025-1029 (1998).

BOOKS OR CHAPTERS PUBLISHED

1. J. D. Maynard, "Acoustical Holography", in the *McGraw-Hill Encyclopedia of Science and Technology*, 7th edition, ed. S. Parker (McGraw-Hill, New York, 1992) p. 86.
2. J. D. Maynard, M. J. McKenna, A. Migliori, and W. M. Visscher, "Ultrasonic Measurements of Elastic Constants in Single Crystals of La_2CuO_4 ", in *Ultrasonics of High-Tc and Other Unconventional Superconductors*, ed. M. Levy, (Academic Press, Boston, 1992) p. 381-408.
3. J. D. Maynard, "Tuning up a quasicrystal", in *Perspectives in Physical Acoustics*, ed Y. Fu, R. K. Sundfors, and P. Suntharothok (World Scientific, Singapore, 1992) p. 201-236.
4. J. D. Maynard, "Learning about phonons with frequencies below one KHz", in *Phonon Scattering in Condensed Matter VII*, ed M. Meissner and R. O. Pohl, (Springer-Verlag, Berlin, 1993) pp. 239-243.
5. J. D. Maynard, "Nearfield acoustic holography and arbitrarily shaped sources", Proceedings of the International Meeting on Acoustical Imaging, Lyon, France, in *Journées Imagerie Acoustique*, ed. Jean-Louis Chauray (1994).

6. J. D. Maynard, "Phonons in Crystals, Quasicrystals, and Anderson Localization", in *Encyclopedia of Acoustics*, ed. M. J. Crocker (John Wiley and Sons, New York, 1997), pp 651-660.
7. J. D. Maynard, "Acoustic Holography", in *Encyclopedia of Acoustics*, ed. M. J. Crocker (John Wiley and Sons, New York, 1997), pp 1281-1290.
8. J. D. Maynard, "Resonant Ultrasound Spectroscopy", in *Medical Imaging 1998: Ultrasonic Transducer Engineering*, ed. K. Kirk Shung (Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1998) pp 132 - 142.
9. J. D. Maynard, "Nearfield acoustic holography and arbitrarily shaped sources and enclosures", in *Proceedings of the Sixth International Congress on Sound and Vibration*, ed. Finn Jacobsen (1999) pp 821 - 828.

PRINTED TECHNICAL REPORTS AND DISSERTATIONS

1. Wei-li Lin, Physics Ph.D. Thesis, 1996; *The Measurement of Ultra Low Optical Absorption in Solids in the Near Infrared Using a Resonant Photoacoustic Technique*.
2. Philip S. Spoor, Physics Ph.D. Thesis, 1997; *Elastic Properties of Novel Materials using PVDF Film and Resonant Ultrasound Spectroscopy*.
3. Philip Jason White, Masters Degree in Acoustics, 1998. *Thin Film Characterization with Resonant Ultrasound Spectroscopy*.
4. Vernon A. Hopkins, Ph.D. Degree in Physics, 1999. *Observation of Nonlinear Pulse Propagation in Disordered Media*.

PAPERS AND BOOK CHAPTERS SUBMITTED

1. J. D. Maynard, "Wave propagation in periodic, random, and quasiperiodic media, with a tutorial on Anderson localization" submitted as a Tutorial Review to J. Acoust. Soc. Am., June, 1997.
2. J. D. Maynard, "Nearfield acoustic holography for arbitrarily shaped sources", submitted to *Proceedings of InterNoise 2000* (2000).
3. J. D. Maynard, "Elastic properties of quasicrystals", *Handbook of Elastic Properties of Materials*, ed. M. Levy (Academic Press, NY).
4. J. D. Maynard, "Acoustic properties of superfluid helium four", *Handbook of Elastic Properties of Materials*, ed. M. Levy (Academic Press, NY).

PATENTS/APPLICATIONS

1. Patent Disclosure, "High Speed Digital Imaging System", September, 1995.
2. Patent Disclosure, "Anisotropic stack/heat-exchangers for thermoacoustic heat engines" (Upgraded version, June, 1997).
3. Patent Number 5,717,266, High Power Oscillatory Drive, February 10, 1998.

INVITED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. Colloquium, Department of Physics, University of Pittsburgh, April 13, 1992, "Non-linearity and Disorder".
2. Invited Lecture, Society of Engineering Science 28th Annual Technical Meeting, University of Florida, Gainesville, November, 1991 "Using Piezoelectric Film and Ultrasound Resonance to Determine the Elastic Tensor of Small Fragile Samples".
3. Invited Lecture, Bolef Symposium in Physical Acoustics, Lake Buena Vista, Florida, December 1991 "Tuning up a Quasicrystal".
4. Invited Symposium Lecture, 123rd Meeting of the Acoust. Soc. Am., Salt Lake City, May 12, 1992 "Nonlinear Effects in Periodic and Disordered Wave media".
5. Invited Lecture, 1992 Physical Acoustics Summer School, Asilomar Conference Center, Pacific Grove, CA, June, 1992, "Linear and nonlinear wave propagation in periodic, random, and quasiperiodic media".
6. Invited lecture, Seventh International Conference on Phonon Scattering in Condensed Matter, Cornell University, August, 1992, "Learning about phonons with frequencies below one KHz".
7. Seminar, Cornell University, Department of Physics, September 8 1992 "Acoustic analogs of mesoscopic systems", David Lee, host.
8. Colloquium, Department of Physics, West Virginia University, December 3, 1992, "Tuning-up a Quasicrystal", Thomas Myers, host.
9. Colloquium, Department of Physics, Washington University, St. Louis, MO January 13, 1993, "Tuning-up a Quasicrystal", J. E. Shrauner, host.
10. Invited Symposium Lecture, 124th Meeting of the Acoustical Society of America, New Orleans, October 1992, "Using piezoelectric film and resonant ultrasound to determine the elastic tensor of small, fragile samples".
11. Invited Symposium Lecture, 125th Meeting of the Acoustical Society of America, Ottawa, Ontario, May, 1993, "Pulses, nonlinearity, and Anderson localization".

12. Invited Lecture, 20th International Meeting of Low Temperature Physics, Eugene, Oregon, August 1993, "Classical analogs of mesoscopic quantum phenomena".
13. Colloquium, Department of Physics, University of Oregon, Eugene, OR, October 7, 1993, Martin Weybourne, host.
14. Colloquium, University of California, Irvine, CA, January 28, 1994 "Tuning-up a quasicrystal".
15. Colloquium, University of Washington, Seattle, WA, January 31, 1994 "Tuning-up a quasicrystal".
16. Invited Symposium Lecture, 125th Meeting of the Acoustical Society of America, Ottawa, Ontario, May, 1993, "Pulses, nonlinearity, and Anderson localization".
17. Invited Lecture, International Meeting on Acoustical Imaging, Lyon, France, March 1, 1994, "Nearfield acoustic holography and arbitrarily shaped sources".
18. Invited Symposium Lecture, APS Meeting, Washington, DC, April 1994 "Disorder and nonlinearity: Studies in liquid helium".
19. Seminar, Penn State University, Department of Engineering Science and Mechanics, University Park, PA, January 26, 1994 "Tuning-up a quasicrystal".
20. Seminar, University of Maryland, Department of Physics, May 3, 1994 "Experimental studies of nonlinearity and disorder", John D. Weeks, host.
21. Lecture series, Physical Acoustics Summer School, Pacific Grove, CA, June 1994, "Periodic, random, and quasiperiodic media".
22. Invited talk, P. S. Spoor and J. D. Maynard, Workshop on Resonant Ultrasound Spectroscopy, University of Wisconsin, MI, August 1994, "Use of Piezoelectric films and RUS on small samples of novel materials".
23. Colloquium, University of Utah, Department of Physics, Salt Lake City, Utah, January 26, 1995, "Tuning-up a Quasicrystal".
24. Seminar, Department of Physics, Ohio State University, Columbus, OH, March 1, 1995, "Tuning-up a Quasicrystal".
25. Seminar, Acoustics Program, Penn State University, University Park, PA February 7, 1995, "Tuning-up a Quasicrystal".
26. Invited Lecture, Society of Physics Students, Zone 3 Meeting, Penn State University, April 8, 1995, "Tuning-up a quasicrystal".
27. Invited talk, Wei-li Lin, "Resonant photoacoustic measurement of optical absorption in solids", J. Acoust. Soc. Am. **97**, 3408 (1995).

28. Colloquium, Dartmouth College, Department of Physics, Hanover, NH, January 12, 1996. "Tuning-up a Quasicrystal".
29. Invited talk, Phil Spoor, Consortium on Resonant Ultrasound Spectroscopy, Santa Fe, NM, August 24-26, 1995. "Numerical anomalies in the Rayleigh-Ritz method for calculating the normal mode vibrations of arbitrarily shaped elastic solids".
30. Invited talk, Phil Spoor, 131st Meeting of the Acoustical Society of America, Indianapolis, IN, May 13-17, 1996. "An investigation of computational problems associated with resonant ultrasound spectroscopy".
31. Lecture Series, 1996 Physical Acoustics Summer School, Asilomar Conference Center, Pacific Grove, CA, June 21-28, 1996. "Periodic, random, and quasiperiodic media".
32. Lecture Series, UCLA Nonlinear Science Summer School, Los Angeles, CA, June 28-29, 1996. "Anderson localization of nonlinear waves".
33. Invited talk, Thermoacoustics Review Meeting, Asilomar Conference Center, Pacific Grove, CA, November 13-15, 1996 "Anisotropic heat-exchanger/stack configurations for thermoacoustic heat engines".
34. Plenary Lecture, XXIII International Meeting on Acoustical Imaging, Boston, MA, April 13-16, 1997. "Acoustic Imaging of Active Sources".
35. Invited talk, Resonance Meeting, Asilomar Conference Center, Pacific Grove, CA, May 11-15, 1997. "Determining the radiation impedance for arbitrarily shaped surfaces".
36. Invited talk, Resonance Meeting, Asilomar Conference Center, Pacific Grove, CA, May 11-15, 1997. "Resonant photoacoustic spectroscopy of optical materials".
37. Colloquium, University of Toronto, Department of Physics, Toronto, CANADA, September 12, 1996. "Tuning-up a quasicrystal".
38. Colloquium, University of Maryland, Department of Physics, College Park, MD 20742-4111, April 22, 1997. "Tuning-up a quasicrystal".
39. Invited Lecture, Medical Imaging 1998, San Diego, CA, February 21-25, 1998, "Resonant ultrasound spectroscopy".
40. Invited Lecture, XXVII International School on Physics of Semiconducting Compounds, Ustron-Jaszowiec, Poland, June 7 - 12, 1998, "Tuning-up a Quasicrystal"
41. Invited Lecture, 1998 Physical Acoustics Summer School, Pacific Grove, CA, June 14-21, 1998. "Tutorial on Quantum Mechanics"
42. Invited Lecture, 1998 Physical Acoustics Summer School, Pacific Grove, CA, June 14-21, 1998. "Periodic, random, and quasiperiodic media".
43. Invited Lecture, 135th Meeting of the Acoustical Society of America, Seattle, WA, June 20-26, 1998. "Isadore Rudnick: Making Waves in Superfluid Helium"

44. Colloquium, Department of Physics, University of California, Berkeley, CA, November 23, 1998. "Tuning-up a Quasicrystal".
45. Invited Lecture, Thermoacoustics Review Meeting 1999, National Center for Physical Acoustics, The University of Mississippi, January 5 - 8, 1999. "Research on an Anisotropic Stack/Heat-exchanger".
46. Invited Presentation, Condensed Matter Physics Exhibition, Centennial Meeting of the American Physical Society of America, Atlanta, GA, March 20-26, 1999, "Classical Anderson Localization".
47. Invited Lecture, 1999 Resonance Meeting, Jammie Whitten Center for Physical Acoustics, University of Mississippi, Oxford, MS, May 31, 1999. "Characterizing thin films with resonant ultrasound spectroscopy".
48. Colloquium, Indiana University of Pennsylvania, Department of Physics, December 3, 1999. "Tuning-up a Quasicrystal".
49. Invited Lecture, Sixth International Conference on Sound and Vibration, July 5-8, 1999, Copenhagen, Denmark, "Nearfield Acoustic Holography and Arbitrarily Shaped Sources and Enclosures".
50. Colloquium, Texas A&M University, Department of Physics, April 6, 2000. "Tuning-up a quasicrystal".
51. Invited lecture, L. C. Krysac, 139th Meeting of the Acoustical Society of America, 2 June, 2000, Atlanta, GA, "Attenuating stress waves during the fracture of a brittle carbon foam using ferrofluid damping".

CONTRIBUTED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. J. D. Maynard and M. J. McKenna, "Experimental Studies of Disorder and Nonlinearity", Bull. Am. Phys. Soc. **37**, 294 (1992).
2. M. J. McKenna, P. S. Spoor, and J. D. Maynard, "Determination of the Elastic Constants of a Single Grain Al-Cu-Li Quasicrystal in a Single Measurement", Bull. Am. Phys. Soc. **37**, 615 (1992).
3. M. J. McKenna, T. P. Brosius, and J. D. Maynard, "An Analysis, in Terms of Quantum Kinks, for a New Growth Mode for Solid 4He on Grafoil", Bull. Am. Phys. Soc. **37**, 951 (1992).
4. J. D. Maynard, "A Possible Explanation for the Discrepancy in Electron Persistent Current Amplitudes: A Superfluid Acoustic Analog", Bull. Am. Phys. Soc. **37**, 969 (1992).

5. J. D. Maynard, "A possible explanation for the discrepancy in electron persistent current amplitudes: A superfluid acoustic analog", Symposium on Quantum Fluids and Solids - 1992, Penn State University, June, 1992.
6. V. A. Hopkins, M. J. McKenna, and J. D. Maynard, "A study of two- dimensional Anderson localization as a function of disorder", Symposium on Quantum Fluids and Solids - 1992, Penn State University, June, 1992.
7. M. J. McKenna, T. P. Brosius, and J. D. Maynard, "An analysis, in terms of quantum kinks, for a new growth mode for solid 4He on Grafoil", Symposium on Quantum Fluids and Solids - 1992, Penn State University, June, 1992.
8. P. S. Spoor, M. J. McKenna, and J. D. Maynard, "Using acoustic resonators to study superfluid-filled silica aerogel, high Tc superconductors, and quasicrystals", Symposium on Quantum Fluids and Solids - 1992, Penn State University, June, 1992.
9. P. S. Spoor, M. J. McKenna, and J. D. Maynard, "Application of resonant ultrasound spectroscopy to the study of small single crystal wafers", J. Acoust. Soc. Am. **92**, 2313 (1992)..
10. J. D. Maynard, J. Keat, and M. J. McKenna, "Experiments on nonlinear pulse propagation in disordered media", Bull. Am. Phys. Soc. **38**, 384 (1993).
11. P. S. Spoor, M. J. McKenna, and J. D. Maynard, "Elastic constants of TiB₂ and SiC using resonant ultrasound spectroscopy", Bull. Am. Phys. Soc. **38**, 677 (1993).
12. M. J. McKenna, P. S. Spoor, and J. D. Maynard, "Elastic constants of quasicrystalline and R-phase cubic AlCuLi using resonant ultrasound spectroscopy", Bull. Am. Phys. Soc. **38**, 681 (1993).
13. V. Hopkins, M. J. McKenna, and J. D. Maynard, "The use of ³He NMR as a probe of the nature of the 4He solid/superfluid interface", Bull. Am. Phys. Soc. **38**, 1042 (1993).
14. M. J. McKenna, M. J. Baloh, and J. D. Maynard, "An annular first, second, and fourth sound resonator for studying the superfluid transition dimensional crossover and finite amplitude effects", Bull. Am. Phys. Soc. **38**, 1042 (1993).
15. P. S. Spoor, M. J. McKenna, and J. D. Maynard, "A comparison of elastic constants of the quasicrystalline and cubic approximant phases of AlCuLi, using resonant ultrasound spectroscopy", J. Acoust. Soc. Am. **93**, 2276 (1993)..
16. M. J. McKenna, Wei-li Lin, and J. D. Maynard, "Using piezoelectric film and resonant ultrasound for photoacoustic measurements of very low optical absorption in piezoelectric and dielectric crystals", J. Acoust. Soc. Am. **93**, 2276 (1993)..
17. P. S. Spoor, M. J. McKenna, and J. D. Maynard, "A comparison of elastic constants of the quasicrystalline and cubic approximant phases of AlCuLi, using resonant ultrasound spectroscopy", J. Acoust. Soc. Am. **93**, 2276 (1993)..

18. V. A. Hopkins, M. J. McKenna, and J. D. Maynard, "Anderson localization of ^3He with variable disorder provided by a ^4He solid/liquid interface, presented at the 20th International Meeting of Low Temperature Physics, Eugene, Oregon, August 1993.
19. M. J. McKenna, J. Keat, J. Wang, and J. D. Maynard, "Experiments on nonlinear wave propagation in disordered media, presented at the 20th International Meeting of Low Temperature Physics, Eugene, Oregon, August 1993.
20. S. R. Savitski and J. D. Maynard, "Observation of Individual Bond Breaking Events in Precursors, Cascades, etc. in the Onset and Progression of Fracture", *Bull. Am. Phys. Soc.* **39**, 860 (1994).
21. P. S. Spoor and J. D. Maynard, "Measurements and Analysis of the anisotropy of the AlCuLi quasicrystal and the related R-phase", *Bull. Am. Phys. Soc.* **39**, 862 (1994).
22. V. A. Hopkins, M. J. McKenna, and J. D. Maynard, "Vortex generation in a capillary array: A reciprocity calibration", *Bull. Am. Phys. Soc.* **39**, 1049 (1994).
23. P. S. Spoor and J. D. Maynard, "Elastic-constant determination of small, near-isotropic crystals using resonant ultrasound spectroscopy: New quasicrystal results", *J. Acoust. Soc. Amer.* **96**, 3226 (1994).
24. T. Zhang, S. R. Savitski, and J. D. Maynard, "Observation of individual bond breaking events in the onset and propagation of fracture", *J. Acoust. Soc. Amer.* **96**, 3227 (1994).
25. L. C. Krysac, T. Zhang, and J. D. Maynard, "The fracture of brittle carbonaceous form as a candidate for a physical realization of the random fuse model for material breakdown", *Bull. Am. Phys. Soc.* **40**, 478 (1995).
26. P. S. Spoor and J. D. Maynard, "Numerical anomalies in the Rayleigh-Ritz method for calculating the normal mode vibrations of arbitrarily shaped elastic solids", *J. Acoust. Soc. Am.* **97**, 3326 (1995).
27. L. C. Krysac and J. D. Maynard, "Detailed observation of the complete fracture process of brittle carbon foam", *J. Acoust. Soc. Amer.* **98**, 2875 (1995). St. Louis, MO, November 27-December 1, 1995.
28. L. C. Krysac and J. D. maynard, "The dynamics of brittle fracture", *Bull. Am. Phys. Soc.* **41**, 314 (1996). St. Louis, MO, March 18-22, 1996.
29. P. S. Spoor and J. D. maynard, "Isotropy and anisotropy in icosahedral and cubic AlCuLi", *Bull. Am. Phys. Soc.* **41**, 787 (1996). St. Louis, MO, March 18-22, 1996.
30. B. Bennett, T. Zhang, V. Hopkins, and J. D. Maynard, "Using liquid helium to study fluid interface coalescence effects", APS Division of Fluid Dynamics, 49th Annual Meeting, Syracuse University, Syracuse, NY 13244, November 23-26, 1996.

31. D. C. Zhang and J. D. Maynard, "High power, high efficiency drives for annular thermoacoustic refrigerators", J. Acoust. Soc. Am. **100**, 2816 (1996). December 2-6, 1996.
32. L. C. Kryszak and J. D. Maynard, "Statistical and deterministic dynamics during fracture of brittle carbon foam", Bull. Am. Phys. Soc. **42**, 460 (1997). Kansas City, MO.
33. B. Bennett, V. Hopkins, T. Zhang, and J. D. Maynard, "Studies of liquid interface impact using helium", Bull. Am. Phys. Soc. **42**, 615 (1997). Kansas City, MO.
34. P. J. White and J. D. Maynard, "Thin film characterization using resonance ultrasound spectroscopy", Resonance Meeting, Asilomar Conference Center, Pacific Grove, CA, May 11-15, 1997.
35. L. C. Kryszak and J. D. Maynard, "The development of self-focused pulses of nonlinear second sound in helium II from delayed edge waves", J. Acoust. Soc. Am. **101**, 3081 (1997), State College, PA.
36. L. C. Kryszak and J. D. Maynard, "Fracture of brittle carbon foam correlated by stress waves", Bull. Am. Phys. Soc. **43**, 98 (1998); Los Angeles, CA.
37. B. Bennett, L. C. Kryszak, and J. D. Maynard, "Noise from raindrops; fundamental studies of bubble entrainment", Bull. Am. Phys. Soc. **43**, 685 (1997); Los Angeles, CA.
38. A. Apostolou, J. So, Z. Lu, and J. D. Maynard, "Bubble entrainment in liquid helium", Bull. Am. Phys. Soc. **45**, 1049 (2000). Minneapolis, MN.

HONORS/AWARDS/PRIZES

1. J. D. Maynard was awarded the Silver Medal in Physical Acoustics by the Acoustical Society of America, November, 1994.
2. Professor Maynard was invited to write a paper for the science magazine *Physics Today*: "Resonant Ultrasound Spectroscopy", [*Physics Today* **49**, 26-31 (1996)].
3. Professor Maynard presented an invited tutorial lecture on Anderson Localization at the prestigious International School on Physics of Semiconducting Compounds, Ustron-Jaszowiec, Poland, June 7 - 12, 1998.
4. Professor Maynard's research on Thermoacoustic Refrigerators was featured in the "Inside R&D" report on technical innovation in the magazine *Technical Insights*, February 18, 1998 (John Wiley & Sons, New York).
5. Professor Maynard was invited to prepare a paper on Acoustic Analogs of Quantum Mechanical Systems for the physics journal *Reviews of Modern Physics*.

6. Professor Maynard was appointed as Divisional Associate Editor for the physics journal *Physical Review Letters*.

GRADUATE STUDENTS SUPPORTED AT LEAST PART TIME

1. Philip Spoor (Ph.D. candidate, acoustics), began Fall 1989, Elastic Constant Measurements for Quasicrystals.
2. Wei-Li Lin (Ph.D. candidate, Physics), began summer 1991, Infrared resonant photoacoustics.
3. Brian Bennett (Ph.D. candidate, Acoustics Program), began summer 1994, Superfluid hydrodynamics in a capillary array.
4. Jason White (Ph.D. candidate, physics), began summer 1994, Resonant Ultrasound Spectroscopy.
5. Vernon A. Hopkins (Ph.D. candidate Physics), began Fall 1989, Nonlinear Pulses in Disordered Media
6. Adonis Apostolou (MS candidate, Acoustics Program), began January, 1999. Bubble entrainment from impacting drops using liquid helium
7. Josh Gladden (Ph.D. candidate, Physics), began summer 1999. Using Resonant Ultrasound Spectroscopy to study thin films

POSTDOCTORALS AT LEAST PARTIALLY SUPPORTED

1. Mark McKenna, Research Associate, July 1, 1989 to July 31, 1993.
2. Tian-ming Zhang, Postdoctoral Scholar, began June, 1994.
3. Cindy Krysa, Postdoctoral Scholar, began July, 1994.
4. Jin-Hyun So, Began summer 1998. Ph.D. Physics, Ohio University, 1998.
5. Zhiqu Lu, Began January 1999. Ph.D. Physics, University of Pau, France, November, 1998.

UNDERGRADUATES INVOLVED IN RESEARCH

1. Ron Stanley, Summer 1991.
2. Brian Pudliner, Summer 1991.
3. Chris Koeppen, Spring 1992.
4. Brian S. Wilson, Spring 1992.
5. Justin Keat, Summer 1992.
6. Michael Baloh, Senior, 1992-94.

7. Steve Savitski, Senior 1994.
8. Rob Bailis, Senior, 1994.
9. Jason White, Summer 1993.
10. Robert McNeese, Summer 1994.
11. Joseph Buck, Junior, 1994-95.
12. John Lelii, NSF Research Experience for Undergraduates (REU), summer 1995.
13. Kirk Fisher, Physics major, 1994-95.
14. Patrick Johnston, 1994-95.
15. Mike Marotta, NSF REU student, summer 1995.
16. Christina D'Arrigo, Women in Science and Engineering Research (WISER) student, 1996,97.
17. Ivonne D'Amato, WISER student, 1996,97.
18. Bill Siddall, NSF REU student, summer 1997.
19. Ben Winjum, NSF REU student, summer 1997.
20. Adam Shumays, Physics major, 1997,98.
21. Jen Linton, WISER student, 1997,98.
22. Jill Kuzo, WISER student, 1997,98.
23. Zigurts Majumdar, REU student, summer 1998.
24. Alan Bishop, Physics major, 1998-99.
25. Jerry Boor, Physics major, 1998.
26. Jennifer Yantorno, NSF REU student, summer 1999.